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Island resource exploitation by the ancient Maya during periods of climate stress, Ambergris Caye, Belize

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ABSTRACT

Ancient Maya societies experienced a period of reorganisation and change in settlement patterns associated with social and climate instability at the end of the Classic period (750-1000 CE) and the subsequent Postclassic period (1200-1500 CE). Although it has been proposed that severe droughts and the breakdown of Classic political systems caused a migration of populations towards the coast, we have little evidence of the nature of land-use at coastal sites. Our understanding of subsistence on islands has been shaped by archaeological research indicating marine-based diets, with maize imported from the mainland. Here we provide, for the first time, palaeoecological proxy data that inform on ancient Maya land-use on an island site, located on Ambergris Caye, Belize. Using pollen and charcoal proxies, we present over 6000 years of environmental change and land-use history. Our reconstruction reveals evidence of cultivation, beginning at 2900 BCE and culminating during the Postclassic Period. We demonstrate that periods of higher land-use intensity correlate with climate instability, which corroborates archaeological evidence of migration to coastal locations. We hypothesize that the diverse marine and terrestrial environments of the island provided sustainable resources for the mainland Maya to use during times of both political and climatic stress.

1. Introduction

The decline of the Classic Maya civilisation has been attributed to a number of environmental and social factors, with high-resolution palaeoenvironmental records revealing climate change as one of the most prominent (Hoggarth et al., 2016; Kennett et al., 2012; Turner and Sabloff, 2012). Whilst the social impacts of severe drought events are becoming evident, there is less attention focused on how subsistence strategies were adapted to mitigate rapid climatic changes. Palaeoecological investigations have addressed questions regarding Maya subsistence and landscape management, such as the first establishment of agriculture (Dunning et al., 1998; Pohl et al., 1996; Rosenswig et al., 2014), the degrees of deforestation associated with the growth of their civilisation (Leyden, 2002; McNeil, 2012), soils and wetland management within the context of environmental change (Krause et al., 2019) and ecosystem response following the abandonment of settlements (Mueller et al., 2010; Turner and Sabloff, 2012; Wahl et al., 2007). The existing palaeoecological studies, however, focus on mainland settlements of the central and southern lowlands which do not account for movement of populations toward coastal regions following periods of mainland abandonment, as proposed by archaeologists (Cucina, 2015; McKillop, 2010; Miller, 1985). Evidence for migration of populations toward the coast and the occupation and use of island sites is based on the development of sophisticated trade networks along the coast and interior rivers (Graham et al., 2017; Graham and Pendergast, 1989; Guderjan, 1995). An investigation of land-use on island settlements provides an important opportunity to understand how these geographically disparate communities interacted, especially during times of socio-political destabilisation and social transformation on the mainland.

Subsistence on island sites has primarily been linked to archaeological evidence for marine-based diets, with trade networks establishing a route for surplus food staples (Graham et al., 2017; Parker, 2011). These items would have been vital, since subsistence strategies of island inhabitants were largely marine-based and maize was likely imported from the mainland (Graham et al., 2017; Parker, 2011). However, whether cultivation occurred on island sites has hitherto not been tested using palaeoecological methods. Given the increased importance of maritime exchange and evidence for expansion of settlements during the Postclassic Period, we investigate the ways in which the ancient Maya

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exploited and modified their landscapes after the large-scale abandonment of interior centres during the Terminal Classic and Postclassic periods. Ambergris Caye, an island off the main coast of Belize, has limited suitable land for cultivation due to the dominance of mangroves. However, evidence for ancient Maya soil management techniques suggest that these environments were possibly used for local subsistence (Graham et al., 2017). The north of the island is dominated by seasonally dry *terra firme* tropical forest, which may have been used for maize cultivation during the Postclassic Period (*ca.* 1200-1500 CE) (Guderjan, 1995). Ambergris Caye, thus, offers a unique opportunity to examine the land-use strategies of Pre-Columbian societies in an island environment.

1.1. Study context

The island of Ambergris Caye (Fig. 1) is 40 km long and <7 km wide and is located off the eastern coast of Belize. Large-scale climate variability is driven by the Intertropical Convergence Zone (ITCZ), characterised by a north/southwards migration which produces a distinct seasonality in precipitation. The dry season generally falls between January and April, with the wet season most pronounced between May and December. Mangrove and littoral forest dominate the island, but seasonally dry tropical forest (SDTF) is located on *terra firme* in the north centre of the island. Key components of the seasonally dry tropical forest community are *Bursera simaruba*, *Gymnopodium floribundum* and *Metopium brownei* (Meerman, 2005) (Fig. 1). Investigations into settlements on Ambergris Caye have identified twenty-two known archaeological sites as part of the Ambergris Caye Archaeological Project (Guderjan, 1995). Of these, only four have been intensively examined or dated (Graham et al., 2017; Guderjan, 1995; Parker, 2011, Williams et al., 2009). According to these studies, the southern site of Marco Gonzalez has the first evidence of construction on the island by *ca.* 300 BCE (Graham et al., 2017). Many other sites, especially along the western coast, were occupied during the Late Classic Period (*ca.* 600-750 CE) (Guderjan, 1995). The establishment of these sites is thought to have been driven by growing trade exchange with the mainland (Guderjan, 1995). Stable isotope analysis of human bones show evidence that

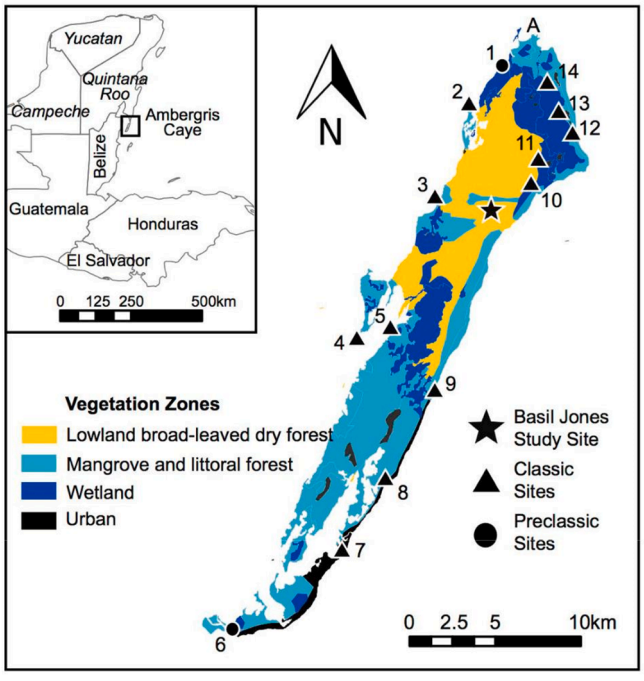

Fig. 1. Map of Ambergris Caye, Belize, with vegetation zones (Meerman, 2005) and Archaeological sites (Guderjan, 1995; Graham et al., 2017). 1. Chac Balam, 2. San Juan, 3. Santa Cruz, 4. Yalamha, 5. Laguna de Cayo Francesca, 6. Marco Gonzalez, 7. San Juan.

inhabitants at these coastal sites had predominantly marine-based diets (Parker, 2011), whilst inhabitants at Marco Gonzalez show a high proportion of maize consumption (Williams et al., 2009). Strong trade ties between Marco Gonzalez and the mainland are thought to have resulted in the import of maize to the site (Graham et al., 2017; Williams et al., 2009).

Located in the northern dry forest ecoregion of Ambergris Caye, the site of Basil Jones is an ideal setting to understand ancient island land-use practices because of its unique setting among tropical dry forest ecosystem, which is limited on the island. Modern-day Basil Jones covers 3 km^2 consisting of seaward beaches, dry forest vegetation and leeward mangrove swamps. The site has the Maya name of Bercellon, differentiating the archaeological site from the wider Basil Jones area, but for the purpose of this study we will refer to the entire site as Basil Jones. Archaeological research has identified the presence of field walls, argued to have been constructed in the Postclassic, indicates some degree of occupation (Guderjan, 1995). A sinkhole adjacent to the Basil Jones archaeological site represents one of few freshwater sources on the island, but it remains to be investigated whether the waterhole is an *aguada*, artificially modified (not connected to water table), or a natural *cenote* (connected to water table).

2. Materials and methods

2.1. Field methods

A 350 cm sediment core was extracted in 50-cm sections from the centre of the Basil Jones sinkhole in 2016 using a Russian corer. An overlap core was also extracted but not analysed. The core site in the interior of the sinkhole was overgrown with semi-aquatic herbaceous vegetation at the time of sampling and the sinkhole was surrounded by fringing palms and riparian shrubs. The sediment cores were extruded into plastic guttering and sedimentology was logged in the field and later confirmed in a laboratory setting. Extracted cores were wrapped in cling film and heavy plastic 'lay flat' core wrap and shipped to Northumbria University. Cores and subsampled sediments were stored at 4 °C.

2.2. Laboratory methods

Nine accelerator mass spectrometry (AMS) radiocarbon (^{14}C) dates were analysed on terrestrial macrofossils from the Basil Jones core. Terrestrial macrofossils were prioritised for dating to reduce the potential risk of offsets caused by the 'old-carbon' effect, which results from the underlying calcareous bedrock. Roots, which would potentially yield younger ^{14}C ages were avoided. When no other material was available, charred macrofossils were included for dating. Radiocarbon results are provided by the NERC radiocarbon facility (eight samples) and the Silesian University of Technology (one sample) (Table 1). Dates were calibrated using the northern hemisphere IntCal13 calibration curve and Post-Bomb northern hemisphere (Reimer et al., 2013), and corrected dates were modelled against depth using the smoothing spline method in the R package 'Clam' (Blaauw, 2010) (Fig. 2).

Twenty-eight sediment samples were selected for pollen analysis. Sampling resolution was focused on prioritising key periods of the period associated with ancient Maya activity. Low-resolution sampling (20-cm intervals) was completed on the upper (0–60 cm) and lower (340–200 cm) parts of the core. High-resolution counts were completed at 2-cm (78–82 cm), 5-cm (120–135 cm) and 10-cm (90–110; 150–190 cm) intervals. Sediment was processed using a modified version of the standard pollen preparation protocol (Faegri and Iversen, 1989), where cultigen pollen were isolated using a 53-μm sieve (Whitney et al., 2012). Exotic *Lycopodium* marker tablets (batch #3862) were added to both the coarse (>53 μm) and fine (<53 μm) samples to determine pollen concentrations per cm^3. Samples were mounted in silicone oil and paraffin wax to ensure slide preservation. Due to the relatively poor concentration of pollen grains in the samples, a total of 200 grains were counted

Table 1
Materials and results of AMS radiocarbon dating for the Basil Jones core. *denotes rejected date.

Publication Code	Sample Depth (cm)	Material	$\delta^{13}C_{vpd}$ (‰)	Uncalibrated yrs BP ± 1 σ	Calibrated yr BP ± 1 σ	Calibrated yr BP (mean probability)	Calendar age (1σ range)
SUERC-84523	14–15	Plant Macrofossil	−29	Modern	Modern	Modern	Post 1950
SUERC-83474	50–51	Bark Fragment	−28.5	516 ± 37	346–509	460	1440-1600 CE
UCAIMS-210606	100–101	Plant Macrofossil	NA	1160 ± 25	1254–1608	1420	340-700 CE
UCAIMS-210617	126–127	Plant Macrofossil	NA	2450 ± 25	2021–2422	2220	70-470 BCE
*SUERC-81082	165–166	Plant Macrofossil	−26.9	1192 ± 37	3187–3749	3740	1240-1800 BCE
SUERC-81806	225–226	Plant Macrofossil	−27.7	4575 ± 35	4643–5147	4900	2690-3200BCE
SUERC-81807	240–241	Charcoal	−25.4	4335 ± 37	4905–5297	5100	2960-3350 BCE
SUERC-81808	290–291	Plant Macrofossil	−26	4927 ± 35	5546–5670	5600	3600-3720 BCE
GdA-5491	302–303	Plant Macrofossil	NA	4915 ± 35	5641-5793	5690	3690-3840 BCE

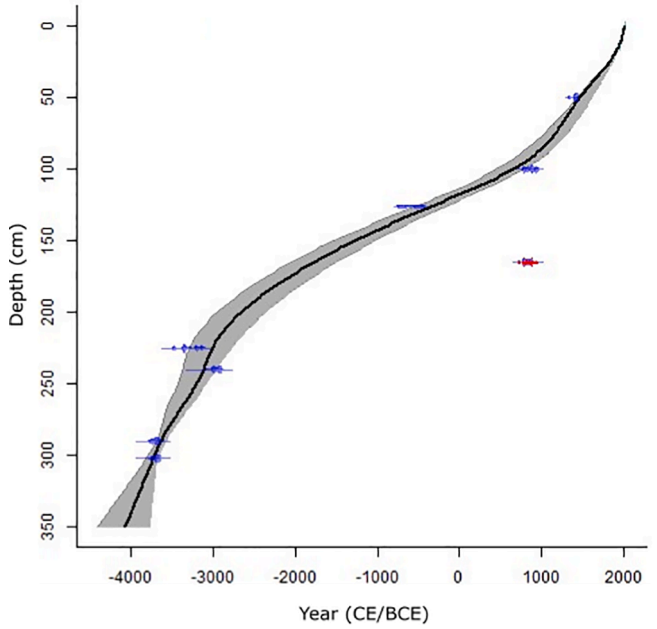

Fig. 2. Age depth model produced by radiocarbon recalibration using the IntCal13 calibration curve in Clam (Blaauw, 2010). Ages are produced to 2σ uncertainty ranges (95th percentile) and presented in BCE/CE. The age highlighted in red was rejected. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

per sample excluding aquatic and local spores.

The spore *Acrostichum aureum* and aquatic taxa were excluded from the total counts and their percentage abundance calculated off total pollen counts (excluding local and aquatic counts). Cyperaceae was included in the sum due to the presence of waterlogged soils in the terrain surrounding the sinkhole. Grains were examined at 400 × and 1000 × magnification using a Leica DM2000 microscope. Identification of pollen grains was achieved using a comparative collection and reference to Palacios-Chávez et al., (1991). The identification of *Zea mays* as a separate species in the Poaceae family was achieved based on the relative size of the grain and the unique exine features (Holst et al., 2007). Charcoal samples were prepared and analysed at a 2 cm resolution throughout the entirety of the core. Preparations used 1-cm^3 of sediment which were deflocculated in 8 ml of 10% KOH in a hot water bath at 90 °C (Whitlock and Larsen, 2002). Samples were then sieved at 125 μm and 250 μm to provide an indication of the local and extra-local charcoal signal, respectively. Pollen and charcoal results are plotted against age in Fig. 3.

2.3. Numerical analyses

To determine the significant pollen zoning boundaries in the record, a binary sum of squares method was employed. Taxa included in zoning analysis occurred at > 5% abundance in at least one sample (Bennett, 1996). All samples were first square-root transformed and zoning. Further analysis of the confidence intervals of each sample was completed using Maher's lognomial distribution in the Psimpoll software programme (Bennett, 2005). To determine the signal recorded in the charcoal record, the charcoal counts were further analysed through the CharAnalysis software (Higuera et al., 2010, 2009). Based on mean sedimentation rate, the record was first resampled to a 1200-year time window. The signal-to-noise (SNI) component of the record identifies fire peaks in the record when SNI > 3 (Higuera et al., 2010; Kelly et al., 2011). Peaks were identified as residual components of the charcoal record where; $C_{peak} = C_{interpolated}\text{-}C_{background}$. Threshold values were defined locally. Peak identification (positive residuals) within the 1200-yr smoothing window were identified as possible fire events at a 95% confidence threshold meaning any minimum charcoal count before a peak has < 5% chance of coming from the same Poisson distribution. Results of CharAnalysis are presented in Fig. 4.

3. Results

3.1. Core lithology and chronology

The Basil Jones core is composed of dark peats. From the base of the core (350 cm) to 300 cm, the peats are mainly black, with high woody components recorded between 335 and 330 and 310–300 cm. From 300 to 200 cm, the core is composed of compact woody brown peat. From 200 to 150 cm, peat becomes less compact and is brown. A short transition to more reddish, rooty, brown peats occurs between 137 and 132 cm. Between 132 and 100 cm, uniform black peat is prominent as a transition is recorded to brown peat once again between 100 and 85 cm. Black peat is once again dominant between 85 and 50 cm, with the remainder of the core (50 cm to surface) dominated by woody black peat. Radiocarbon dating indicates the core spans > 6,000 yrs to present. The age-depth model was constructed using eight AMS radiocarbon dates on terrestrial macrofossil remains (Table 1) and one date was rejected due to its anomalously young age. Dates were extrapolated from 302 cm to the core base due to the lack of available material below this depth.

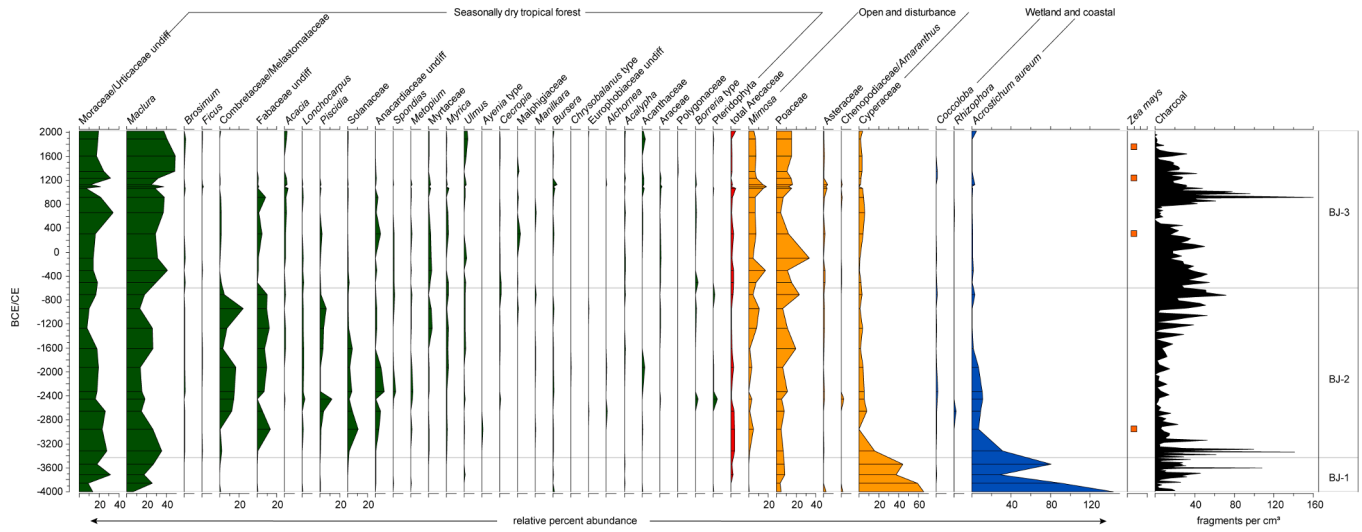

Fig. 3. Pollen and charcoal proxy data for the Basil Jones core. *Zea mays* indicates the presence of maize pollen from these levels and does not indicate abundance or intensity of agriculture. Charcoal concentrations included for the context of land-use.

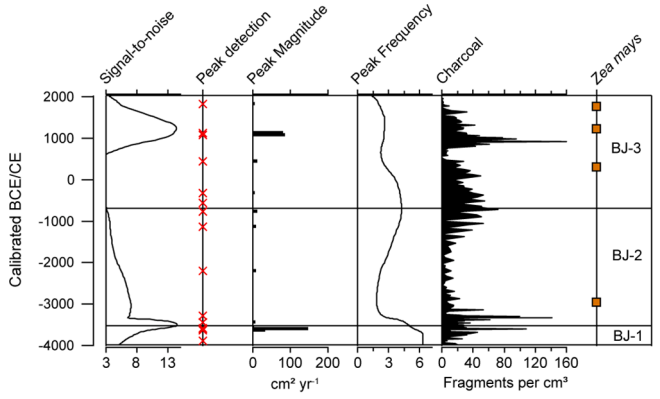

Fig. 4. Results of the CharAnalysis statistical method. (X) represents detectable peaks that pass the 95% threshold and when SNI > 3. Fire frequency (per 1200 years) and peak magnitude also represented. Results described via pollen zonation (BJ-1 to BJ-3).

3.2. Pollen and charcoal analysis

Zonation of the 28 pollen samples produced four statistically significant zones, but the base zone contained one sample (340 cm), so it was combined with the next adjacent zone (320–280 cm) to produce three distinct periods of vegetation community data (BJ1-3) (Fig. 3). To determine the number of peaks in the charcoal record, the charcoal counts were analysed in the CharAnalysis protocol (Higuera et al., 2009), with meaningful peaks confirmed as values of signal-to-noise > 3 (Higuera et al., 2010; Kelly et al., 2011). The results are described by pollen zones (BJ1-3) and are also plotted independently.

Zone BJ1, 340–280 cm, 4000-3600 BCE. BJ1 is dominated by Cyperaceae (65%) and the mangrove-associated fern *Acrostichum aureum* (>100% of the terrestrial pollen sum), with percent abundances gradually decreasing throughout the zone. Forest indicators Moraceae/Urticaceae and openness indicator Poaceae both become more prevalent from 4000 to 3400 BCE. CharAnalysis highlights five fire events between *ca.* 4000-3600 BCE, with one peak showing a high magnitude of 148 $cm^{-2}yr^{-1}$. Fire frequency is constant at six fires per 1200 years throughout the zone.

Zone BJ2, 260–135 cm, 3600-800 BCE. BJ2 contains the first recorded presence of maize (*Zea mays*) in our profile at *ca.* 2900 BCE (1σ, 3100-2500 BCE). Between 3200 and 2000 BCE, a continuous increase in Combretaceae/Melastomataceae pollen is recorded (2–16%) through this zone. At 3200 BCE, high abundances of forest pollen Moraceae/Urticaceae (64%) and sedge Cyperaceae (16%) are recorded, with the latter declining to negligible values after this point. Increases in Fabaceae (~10%) and Solanaceae (~5%), mirrors decreasing Moraceae/Urticaceae abundances between 2800 and 500 BCE, with Poaceae abundances decreasing from high abundances (19%) between 1300 and 500 BCE. Other disturbance indicators, *Mimosa* (17%) and Asteraceae (1%) also decline from 300 BCE through the remainder of the zone. The charcoal data indicate 5 peaks that passed the 95% threshold, but none reach magnitudes of higher than 10 $cm^{-2}yr^{-1}$. Fire frequency varies from 5 to one fire per 1200 years, peaking near the top of the zone.

Zone BJ3, 800 CE to present, 132-0 cm: BJ3 shows the highest occurrence of *Zea mays* in the record at three different horizons (300 CE, 1200 CE and 1760 CE). Combretaceae/Melastomataceae declines to abundances < 1% for the remainder of the record. Poaceae (33%) and *Mimosa* (17%) are recorded in high abundances around 50 BCE and 200 BCE, respectively. Both show a gradual decline, before Poaceae (~15%) remains relatively unvaried for the remainder of the record. *Mimosa* remains constant at 50 BCE to 800 CE (~5%) and then increases to > 10% (max = 18%) until 1000 CE, when it falls below 10% for the rest of the record. Moraceae/Urticaceae shows high abundance (>50%) through the majority of the zone, with minima recorded between 300 BCE-250 CE (45%) and 800–1000 CE (~37%). Through BJ3, seven fire events are recorded. Two high magnitude fire events are recorded (86 and 80 $cm^{-2}yr^{-1}$) approximately 70 years apart. Fire frequency ranges from 4 to 1 fire per 1200 years and declines toward the top of the zone.

4. Discussion

The palaeoecological record at Basil Jones reveals evidence for a tight coupling of periods of fire activity, the presence of cultigen pollen (*Zea mays*) and the composition and abundance of key ecological indicators. The synchronicity between these variables suggests that the major driver for ecological change at Basil Jones was human landscape management. We attribute changes in impact through time to a combination of local island population dynamics and wider scale periods of societal destabilisation, underlain by periods of drought, which influenced how the ancient Maya adapted their subsistence strategies on the island of Ambergris Caye. Archaeologists have previously argued that cultivation on Ambergris Caye was not possible prior to the Postclassic Period (1200-1500 CE), due to the dominance of mangrove ecosystems on the island (Williams et al., 2009). The identification of *Zea mays*

throughout the record counters this long-held hypothesis although the low concentrations of *Zea mays* pollen implies that cultivation was not extensive. Analysis of more sediment cores is needed to understand the past spatial heterogeneity, intensity and diversity of crop production on Ambergris Caye.

Evidence of anthropogenic landscape management is supported by multiple lines of evidence. Firstly, the palaeofire record shows increasing fire activity in close association with the first appearance of *Zea mays* (Fig. 4). As seasonally dry tropical forests are not naturally influenced by regular exposure to fire (Murphy and Lugo, 1986; Pulla et al., 2015), these large, alongside smaller associated peaks, are interpreted as evidence for early swidden (slash and burn) cultivation, a known pre-historic method of landscape management (Borejsza et al., 2011; Dickau et al., 2007). Secondly, the appearance of *Zea mays* on Ambergris Caye (2900 BCE) is closely associated with palaeoecological evidence showing its first appearance in Belize (3000 BCE) (Pohl et al., 1996) and Guatemala (2400 BCE) (Wahl et al., 2007), highlighting that cultivation practices could have been transferred from the mainland to the island. The identification of cultivation at 2900 BCE provides a new chronological baseline for island activity, which predates archaeological interpretations for island activity by>2000 years (Graham et al., 2017).

Following the initial period of cultivation, we infer that land-use declined from 2500 BCE onwards, indicated by the absence of cultigen pollen, declining fire activity and the establishment of arboreal taxa. Due to the lack of archaeological evidence from this period of settlement (*ca.* 2500 BCE) it is difficult to define the driver of this decline in land use, but it is possible that the decreasing exploitation of the dry forest ecosystem reflects a reorganisation of human activity to elsewhere on the island or mainland sites in the early Preclassic period. The earliest evidence for constructed settlements on the island does not occur until 600-300 BCE at Marco Gonzalez, although evidence of earlier occupation may be currently under water which has thus far limited investigations (Graham et al., 2017). The next detectable period of *Zea mays* cultivation on the island began at 300 CE (1σ 125-450 CE) which is accompanied by minimal impact on the forest composition, but evidence for grass pollen (Poaceae) likely represents a degree of landscape opening for maize cultivation.

During the Early and Late Classic periods (*ca.* 300-750 CE) archaeological evidence has been identified on the coast of Ambergris Caye, with largely marine-based diets detected from the inhabitants of San Juan and Chac Balam (Guderjan, 1995; Parker, 2011). However, in the mangrove-dominated south of the island, macrofossil maize cupules from Marco Gonzalez have been dated to approximately 1-250 CE (Graham et al., 2017). These have been previously hypothesised to have been sourced from the mainland (Graham et al., 2017) through trade networks, however, the synchronicity between the maize cupules from Marco Gonzalez and maize pollen evidence at Basil Jones suggests an island origin. Stable isotope analysis of skeletal remains has shown that maize was a component of the diets of inhabitants at San Juan and Chac Balam (Guderjan, 1995; Parker, 2011), although less so than at Marco Gonzalez. Potentially a large proportion of maize consumed at this time on the island was sourced through land-use in the northern dry forest, rather than mainland trade relationships.

The evidence presented here shows that terrestrial ecosystems were managed by the ancient Maya on Ambergris Caye. However, with archaeological evidence highlighting that diets were primarily marine based (Graham et al., 2017; Parker, 2011; Williams et al., 2009), the use of these ecosystems may reflect important events where diversification of subsistence was required. The Preclassic abandonment period (*ca.* 150-250 CE) was a time of political destabilisation that saw the abandonment of many mainland centres, closely chronologically linked with a multi-centennial scale drought (Medina-Elizalde et al., 2016; Webster et al., 2007). The Terminal Preclassic was not homogenous across mainland settlements, as coastal mainland sites such as Colha and Moho Cay became increasingly important (McKillop, 2010). These centres were likely responsible for the trade networks developed along the Caribbean coast, exchanging commodities such as salt and obsidian (McKillop, 2010). On Ambergris Caye, evidence for long-distance exchange is apparent at Marco Gonzalez by *ca.* 200 CE (Graham et al., 2017), as ceramics imported from the mainland are found on other island settlements such as Yalamha and Laguna de Cayo Francesca (Guderjan, 1995).

Archaeological evidence indicates that settlement did not occur at Basil Jones during the Preclassic, although this research shows that land-use was evident by 300 CE (1σ 125-450 CE). Based on the available evidence it is hypothesised that island populations cultivated the dry forest ecosystem to complement their marine based subsistence. The addition of *Zea mays* to the existing subsistence strategies may have been driven by the period of destabilisation (both climatic and political) associated with the Preclassic abandonment period. Direct evidence for this diversification during destabilisation is seen in the correlations between *Zea mays* cultivation in the dry forest, macrofossil evidence for maize consumption in the coastal settlement of Marco Gonzalez (Graham et al., 2017) and the aforementioned evidence for drought (Medina-Elizalde et al., 2016; Webster et al., 2007) (Fig. 5). As previous evidence has shown a strong marine based subsistence for inhabitants at Marco Gonzalez (Graham et al., 2017; Williams et al., 2009), the largest settlement on the island was likely impacted by the destabilisation, resulting in increasing exploitation of the dry forests.

Cultivation during the Preclassic Abandonment Period was not the only evidence that shows a strong synchronicity between mainland instability and land-use in the terrestrial dry forest of Ambergris Caye. The Terminal Classic (*ca.* 750-1000 CE) showed a period of political destabilisation on the mainland, again closely associated with high-intensity drought events (Aimers, 2007; Demarest et al., 2004; Hodell et al., 1995; Kennett et al., 2012; Kennett and Hodell, 2017) which may also have been associated with internal island reorganisation (Guderjan, 1995). The palaeoecological record from Basil Jones shows increasing fire activity during the Terminal Classic (Fig. 5), potentially indicating increasing land use and resource extraction from the freshwater sinkhole. Following the Terminal Classic, the Postclassic (*ca.* 1200-1500 CE) is the only period that shows increasing use of the terrestrial dry forest ecosystem that aligns with archaeological evidence for occupation at Basil Jones. The palaeoecological evidence indicates the highest decline in forest taxa abundance (Moraceae/Urticaceae) and an increase in the disturbance/openness indicators (*Mimosa*, Poaceae), which are closely tied with heightened fire activity and the cultivation of *Zea mays* (*ca.* 1200 CE). Following the collapse of the Classic Maya political system and the depopulation of some lowland centres (*ca.* 750-1000 CE), the Postclassic period saw the re-organisation of mainland communities in settlements along the coast and near water bodies (Cucina, 2015; Miller, 1985; Webster et al., 2007). As populations moved towards island and coastal locations, existing land-use strategies likely became more intensified at Basil Jones, explaining the heightened period of environmental change recorded.

5. Conclusions

The palaeoecological record presented here identifies a complex history of human-environmental interactions associated with the ancient Maya on the island of Ambergis Caye. Evidence for *Zea mays* cultivation predates archaeological research for initial island occupation by almost 2000 years and improves the understanding of the role of the dry forest ecosystem in the mixed subsistence strategies of the ancient Maya. Direct evidence has been established for land-use in the Preclassic in the north of the island, previously thought to have been limited to the Postclassic, with further work needed to improve understanding of the diversity of past coastal ecosystem exploitation and management on the island. Coastal settlements on the island, such as Marco Gonzalez, consumed maize on the island during the Preclassic abandonment period, now shown to have been sourced locally, as well as through mainland trading. Following the large-scale abandonment of centres

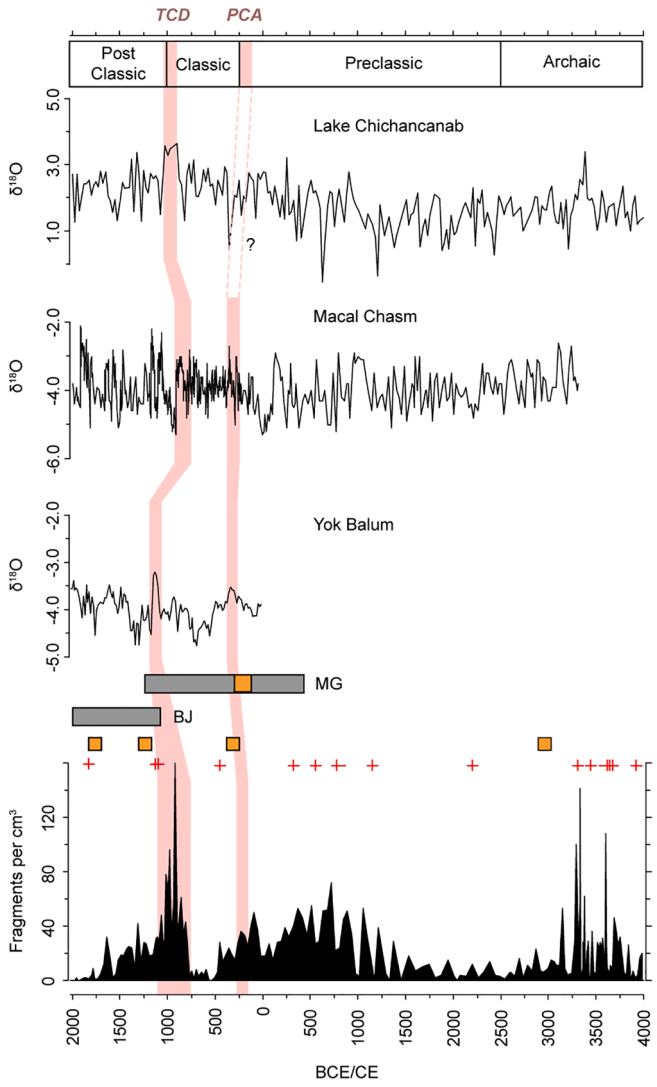

Fig. 5. Summary of palaeoecological record from Basil Jones plotted with palaeoclimate records from the Yucatán peninsula. Presence of maize is shown for Basil Jones (□) along with charcoal counts and peak (+) from CharAnalysis. Grey boxes show archaeological record for the occupation of Basil Jones (Guderjan, 1995) and Marco Gonzalez, with orange box showing macrofossil maize cupule found at Marco Gonzalez (*ca.* 1–250 CE). Red bars show drought events recorded from the palaeoclimate records ($\delta^{18}O$) from the Lake Chichancanab (Hodell et al., 1995), Macal Chasm (Webster et al., 2007) and Yok Balum (Kennett et al., 2012) during the Terminal Classic drought (denoted 'TCD') (ca 750–1100 CE) and Preclassic abandonment ('PCA') (*ca.* 150-250CE). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

during the Terminal Classic Period (*ca.* 750-1000 CE), large scale migration occurred towards the Caribbean coastal regions, including Ambergris Caye. This period of reorganisation saw higher forest impacts at Basil Jones, interpreted to reflect increasing land-use on the island. A strong synchronicity between land-use on the island, regional drought events and the associated periods of political destabilisation suggests that a diversity of subsistence strategies may have mitigated the impacts of climate instability and provided a climate refuge for some mainland communities.

6. Lay summary

Ambergris Caye is one of the largest islands that was inhabited by the ancient Maya. The diets of these island occupants were marine-based and archaeologists think the ancient Maya supplemented their diets with maize imported from the mainland. By examining microfossils preserved in a 6000 year old sediment core, this study shows that the *terra firme* dry forest region in the north of the island was cultivated for maize, and also that this food production occurred earlier than archaeological evidence of habitation. We hypothesise that during times of drought, the cultivation of maize within the dry forest was part of the diverse strategies available to limit the impact caused by the change in climate.

CRediT authorship contribution statement

Adam Bermingham: Conceptualization, Methodology, Investigation, Funding acquisition, Writing - original draft. **Bronwen S. Whitney:** Supervision, Writing - review & editing, Funding acquisition. **Nicholas J.D. Loughlin:** Supervision, Writing - review & editing. **Julie A. Hoggarth:** Conceptualization, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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